Renewable and Sustainable Energy Reviews 15 (2011) 3112–3120

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A review of sustainable cooling technologies in buildings

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ARTICLE INFO

Article history:
Received 18 February 2011
Accepted 21 March 2011
Available online 11 May 2011

Keywords:
Absorption cooling
Coefficient of performance
Desiccant cooling
Stack
Ventilation rate
Wind tower

ABSTRACT

Heating, ventilating and air-conditioning (HVAC) systems play a vital part in ensuring the required comfort levels of residents inside building environments. However, most modern cooling equipments consume high levels of electrical power, thus create high energy consumption rates in buildings. The purpose of this review is to evaluate the common practice of implementing passive and active cooling technologies in buildings. Basic description along with the features and limitations of the techniques are outlined. Comparisons made on the electricity consumption and the capital expenditure has also been proposed. Alternatives such as utilizing heat-pipe heat exchangers for energy recovery have been described. The review highlights that wind towers are prospective alternatives to meet the demand of urban electricity utility along with its contribution to green building.

Contents

1. Introduction

Buildings utilize energy in two primary methodologies, first, to keep the interior as contented as achievable through optimizing heating, ventilation and air-conditioning (HVAC) and secondly, to generate power to run the required domestic applications, all of which leading to an increase in resultant global CO_2 emissions. Buildings are accountable for almost 40% of the global energy consumption and are responsible for almost 40–50% of the world's green house gas emissions [1,2].

In areas of hot climatic conditions and high-humidity, ventilation is predominantly significant in reducing the discomfort levels

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1364-0321/$ – see front matter
doi:10.1016/j.rser.2011.03.032

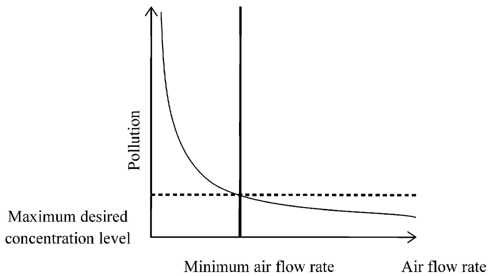


Fig. 1. Natural ventilation for indoor air quality [4].

from moist human skin due to an increase in air velocity over the body [3]. Buildings consume a major load of the utilization of energy; therefore there is a constant feasibility scope for a reduction in the energy consumption using various active and passive cooling techniques to be identified.

Suitable planning of energy-cognizant buildings requires a balance between the thermal performance of the building and the appropriate selection of techniques for heating and cooling. It also necessitates thermal comfort which comes from an adequate quality of the indoor climate. Utilizing natural ventilation for maintaining satisfactory air quality in the interior is dependent on the supply of fresh air. The quantity of ventilation needed to ensure an adequate air quality indoors depends on the amount of the pollutant in a space. It is known that the pollution level decreases exponentially with the airflow rate. Hence, the ideal airflow rate can be calculated by knowing the pollution intensity of the system [4]. Fig. 1 displays the exponential rate of pollution with increasing flow rate.

2. Cooling strategies for air conditioning in buildings

Building cooling technologies comprise of two logical strategies, namely passive and active. Passive cooling involves the cooling of a building feature without the utilization of mechanical apparatus that consume power. The urban microclimate is a major factor in the operational performance of passive cooling technologies in commercial buildings.

One major aspect of integrating passive cooling in buildings is reducing cooling loads or minimizing heat gains. Majority of cooling load in a building comprises of lighting and solar gains. Therefore, a reduction in solar heat gains using simple techniques such as correct insulation and overhangs can substantially increase the energy efficiency of the building and reduce the cooling load [5].

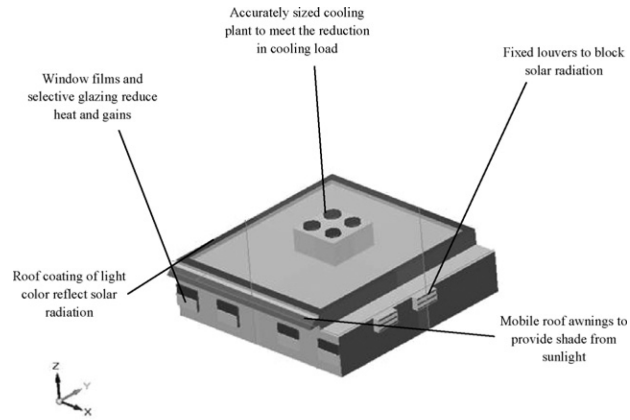


Fig. 3. General techniques to reduce cooling load in a commercial building.

Becker and Paciuk [6] studied various ventilation and pre-cooling strategies and its overall effect on the energy utilization and thermal performance to reduce the energy demands in buildings. The research incorporated simulations on assorted features of the building envelope for varying internal heat loads. The results showed that concentrated night pre-cooling is extremely efficient cooling technique for buildings with high internal heat loads since it reduced the internal mass temperature below the air temperature, consequently decreasing the peak power requirements.

Buoyancy and wind are the foremost driving forces for the working of all natural ventilation techniques and strategies, which include namely wind-variation induced single-sided ventilation, wind-pressure driven cross ventilation and buoyancy pressure-driven stack ventilation. Fig. 2 displays the respective natural ventilation strategies commonly used to reduce solar gains in commercial residences.

On the contrary, if a building cannot be cooled using passive means, the active cooling strategies need consideration. In today's market, major cooling systems are electrically driven compression chillers which have an average coefficient of performance of the installed systems in the range of 3.0–5.0 [8].

Fig. 3 displays some of the common techniques to reduce heat loads. From a general perspective, in warm climates, cooling during the day causes peak energy demands, which results in high expenses of generating the required electricity. In comparison with other time periods, electricity consumption during the night is significantly lower due to the cooler temperatures outside. Various strategies in buildings are already being practiced which exploit

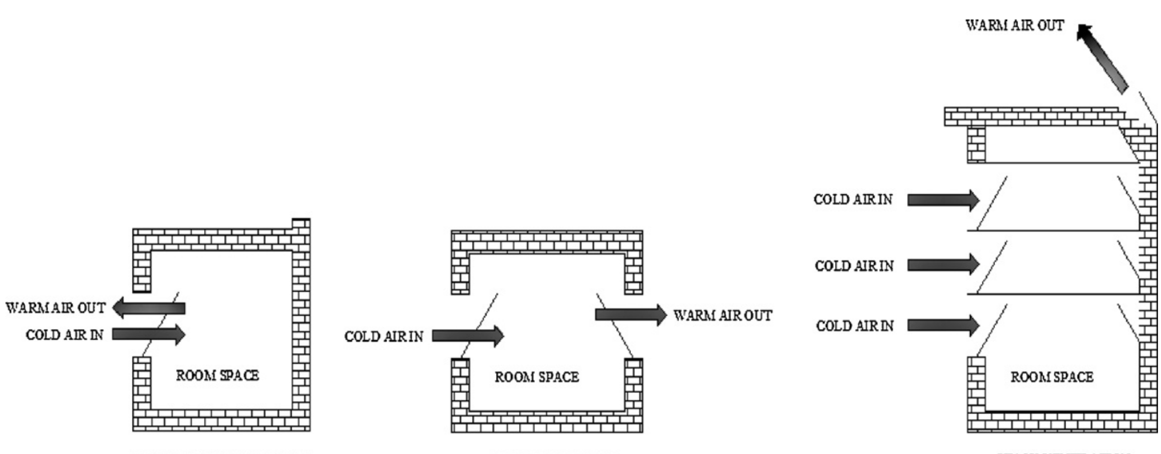


Fig. 2. Natural ventilation common concepts [7].

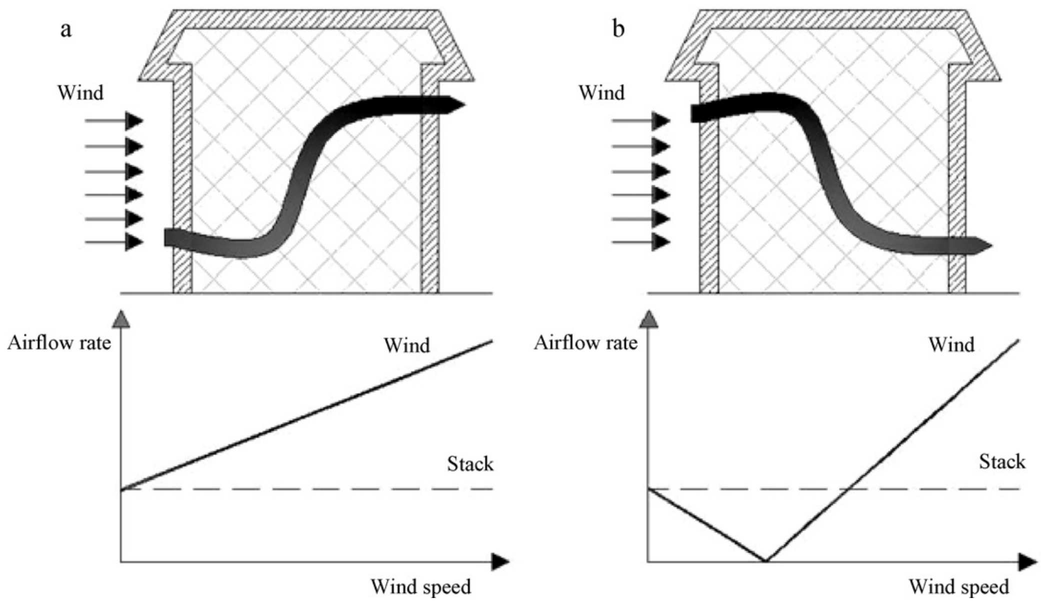


Fig. 4. Combined effects of wind and stack: (a) adding the effects of wind and stack; (b) opposite effects of wind and stack [9].

parameters based on temperatures and wind velocities to reduce the cooling loads for buildings in order to limit the expense for supplementary power consumption.

3. Design guiding principles for passive cooling

Having considered the properties of various common strategies to reduce heat gains, it is essential to study passive cooling principles comprehensively. In regions where there is a significant temperature difference between night and day, passive cooling through natural ventilation is one of the most viable techniques in order to reduce heat gains of a building. In order to implement passive cooling effectively, various direct and indirect factors need to be taken into contemplation for optimized results.

i. Thermal insulation: The fundamental necessity for implementing effective passive cooling technique is to minimize the heat gains during the day. This involves, that the building should have good thermal insulation to avoid hot air from entering the building space.
ii. Climatic variation: In order to utilize the exterior air during the night, the temperature swing should be large and the humidity level should be in the range of comfort. Further, the dew point of the outdoor air must be lower than the internal temperature to circumvent water vapor condensation hazard.
iii. Internal gains: Inappropriate use of electrical appliance such as computers increases the interior temperature of the building space. Hence, energy efficient machines should be made use of to limit the internal gains. Electrochromic glazing technology can be particularly useful in controlling the amount of heat and light that passes through the windows and therefore assists in reduction of the use of electricity for lighting during the daytime.
iv. Ventilation rate: Good wind speeds along with appropriate sizing and location of the vents are important to eradicate the heat stored during the day time and provide ventilation. However, if there is no wind, buoyancy driven stack ventilation can be utilized for the same purpose. It is also important to ensure that the neutral pressure level is as high as possible in order to provide fresh air to most parts of the building space.

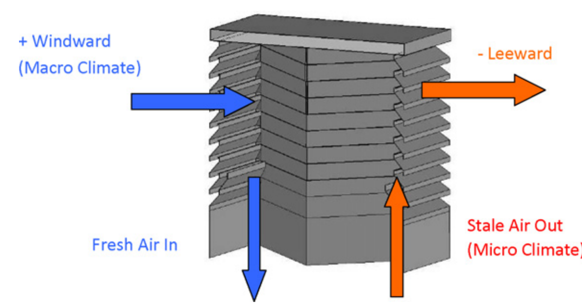


Fig. 5. Cross section of a commercial wind tower.

Therefore, by regulating the internal and external heat gains to a minimum, and with climatic changes within the limits of comfort, the building structure can be cooled with large ventilation rates attained by natural ventilation through doors and windows. This is achieved when the outdoor temperature is lower than the interior temperature of the space since it also accommodates the effect of stack. In situations where the indoor air is warmer than outdoor air, stack effect drives the airflow from bottom to top, with the wind driving the airflow from windward side to the leeward side of the building. Therefore, with the suitable location of vents, the stack effect is added to the pressure of the wind and ventilation is reinforced as displayed in Fig. 4 [9].

The following section highlights some of the active and passive existing cooling technologies in operation on a global scale to reduce air-conditioning loads in building structures, thus limiting the expenses of utilizing electricity for power generation.

4. Passive cooling techniques based on climatological parameters

4.1. Night ventilation

Night ventilation is a passive cooling strategy that makes use of natural ventilation for functioning. This form of passive cooling relies solely on buoyancy or wind-driven natural forces. The thermal comfort during the day is provided by cooling the surface fabric of the building during the night time, which results

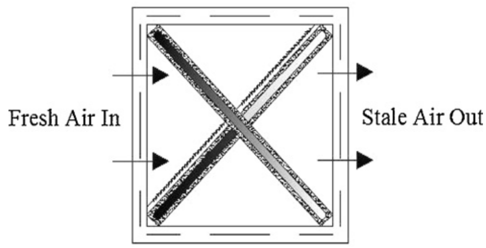


Fig. 6. Plan view of a four-sided windcatcher arrangement: (1) casing, (2) insulation, (3) O/A damper, (4) R/A damper, (5) pre-fill, (6) medium filter, (7) common coil, (8) humidifier, (9) supply fan, (10) motor, (11) isolator, (12) drain pan, (13) drain socket, (14) access door and (15) base.

in heat absorption during the day time. Geros et al. [10] carried out research on the efficiency of night ventilation techniques in 10 urban canyons, situated in Greece. The impact of built-up environment on the utilization of night ventilation was studied. The results confirmed that the energy conservation caused by night ventilation in air-conditioned buildings can be reduced up to 90%. The study also displayed that that due to decrease in wind velocity inside the geometry and an increase in air temperature, the efficiency of the techniques under investigation is decreased. However, Wang et al. [11] investigated the feasibility of operating night ventilation for office buildings in China. The ventilation rates along with the climatic data were analyzed. The results concluded that the efficiency of using this passive cooling technique is higher when the active cooling time is almost equal to the ventilation operation time. The study concluded that the mean radiant temperature of the interiors was reduced up to 3.9 °C with the night ventilation rate of 10 air changes per hour (ach).

4.2. Wind towers

Wind towers are one of the traditional passive cooling techniques for providing natural ventilation. The wind towers were utilized in building geometry in the Middle East for more than three thousand years [12]. Commercial wind vents are divided into quadrants, which allow fresh air to enter as well as stale (used) air to escape irrespective of the prevailing wind direction, shown in Fig. 5.

There are two driving forces for the wind vent. The primary force provides fresh air driven by the positive air pressure on windward side, exhausting stale air with the assistance of the suction pressure on the leeward side. The secondary force is temperature driven and termed “the stack effect”. The density of air is less as its temperature increases causing layers of air to be stacked. The internal and external temperature difference (micro to macro climate) drives the airflow through the ventilator. If the external temperature is lower than the internal temperature, then the buoyancy of the warmer air causes it to rise and exhaust through the unit.

In contemporary wind towers, the principles of passive stack and wind effect are researched in the design of the stack. Li and Mak [12] studied the performance analysis of implementing a windcatcher system using computational fluid dynamics (CFDs) and wind tunnel testing. Various wind velocities and directions were put into the wind tunnel experiments and comparison between experimental and numerical results was compared. The investigation revealed that the performance of the windcatcher is largely manipulated by external velocity and direction of the wind and the flow rate of the air entering the interior are increased with the external wind velocity. The study also revealed that the flow rate reduces with the incidence angle of the wind when the wind velocity is less than 3 m/s. Fig. 6 display the plan view of a four-sided windcatcher.

Montazeri and Azizian [13] researched a one-sided wind catcher for capturing and induction of external air into an urban geometry for the implementation of passive cooling. The study is based on geographical dimensions of the locality and a 1:40 simplified scale model is built and tested. The results determined the positive performance of one-sided wind catcher on the building ventilation design and the maximum efficiency is obtained at zero air incident angle.

Hughes and Ghani [14] studied the consequences on the indoor environment with the usage of windvent dampers which work on the principle of difference in pressure gradient. The investigation was based on highlighting the optimum operating conditions for this passive ventilation device. Computational fluid dynamics was used for numerical analysis for damper angle range between 0 and 90°. The results displayed that the best operation occurs between the range of 45–55° for mean U.K. wind velocities. Hughes and Ghani [15] carried out work on determining the overall feasibility of sustainable development by decreasing the running expenses of buildings. A passive ventilation device known as windvent was used in the computational fluid dynamics based numerical analysis of wind velocities ranging between 1 and 5 m/s. The investigation confirmed that even at low wind velocities, the windvent was able to provide the desired rate of fresh air supply into the building, hence concluding that the device is suitable for sustainable ventilation systems.

Hughes and Ghani [16] also calculated the capability of a passive windcatcher device to achieve the required delivery rates of fresh air intake. The numerical model was based on CFD code and included a standard passive stack device along with simulated low-voltage axial fan. The results established that a low-power fan is mandatory to provide the British Standard requirements of 20 Pa for the minimum ventilation rates. The location of the fan was found to be top position by doing the CFD analysis. The computational work was compared with experimental testing for the confirmation of the investigation. Further study by Hughes and Ghani [17] included the performance analysis of the Windvent device by shifting the external angle of the louvre between 0 and 45° in order to determine the point of highest efficiency in terms of pressure and velocity. The work incorporated a CFD based numerical code with the inlet wind velocity of 4.5 m/s. The results confirmed that an angle of 35° was required for optimized Windvent louvre performance for the input parameters. The study also revealed that there is an increase in velocity of a given space for a reduction in trailing edge stall.

5. Active cooling techniques used in modern buildings

5.1. Packaged terminal air conditioners

Standard room air conditioners are the most common active cooling techniques in practice. A packaged terminal air conditioner (PTAC), more commonly known as a split air conditioning system is generally used in commercial buildings. The PTAC’s consist of two terminal packages, with the condensing system on the outdoors and the evaporative system on the indoors. Yika et al. [18] analyzed the energy efficiency of comparing water-cooled air-conditioning systems (WACS) to air-cooled air-conditioning system (AACS) in commercial buildings in Hong Kong. The work revealed that there is a considerable difference in the application of the two studied systems with reference to the energy consumption in buildings. The study concluded that WACS have a greater efficiency and the implementation of district cooling systems would generate better feasibility, but would require a substantial investment on capital and resources.

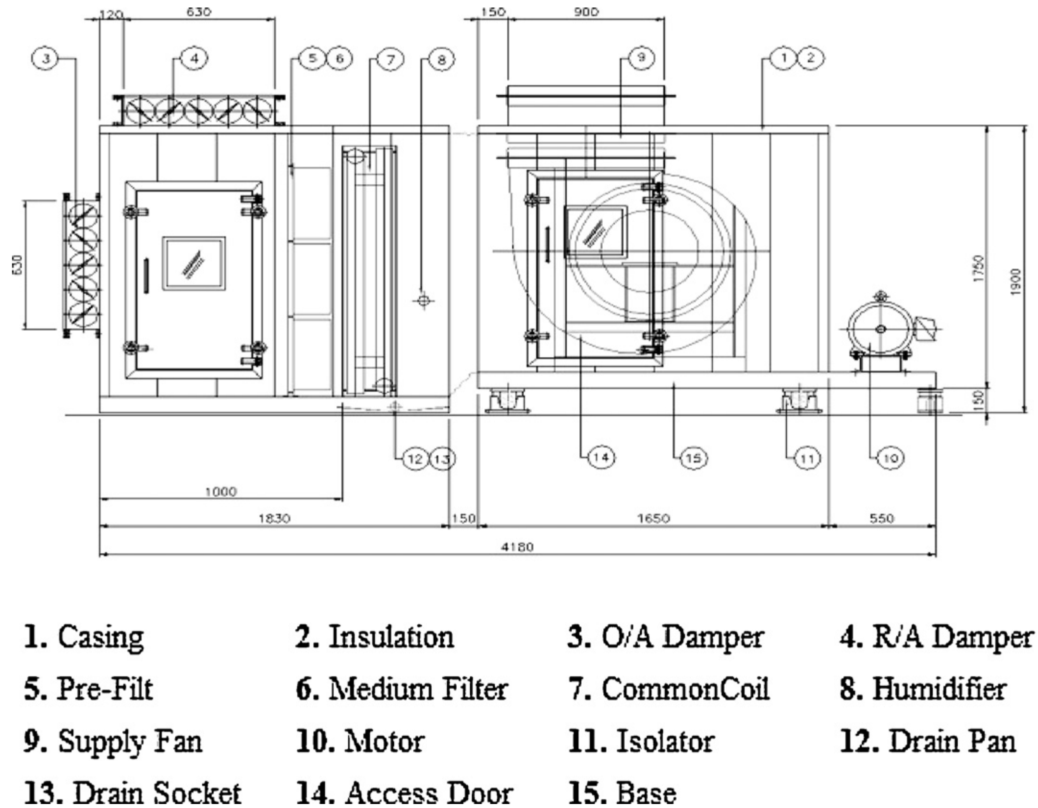


Fig. 7. Mechanical components of an air handling unit [22].

Zhao et al. [19] studied the broad feasibility of implementing dew point evaporative cooling for air-conditioning systems in buildings in China. The climatic conditions including the humidity were analyzed. The work concluded that while the dew point air conditioning system was operational for regions that encountered low humidity, the system was non-functional in regions that encountered high humidity levels, therefore leading to the implementation of a pre-dehumidification device which resulted in further capital investment.

5.2. Air handling units

Air handing units (AHU's) are one of the more extensively used technologies in modern commercial residences. These machines are useful in circulating and conditioning the air in the HVAC system of the geometry. The major mechanical components comprise of a fan compartment, a supply duct and a heating or cooling coil. Kusiak and Li [20] investigated the optimization of the cooling output of an air handling unit using the data mining algorithms in application with the cooling output and the humidity variables. The results confirmed that there was a reduction in the cooling output while the supply air temperature and humidity remained in the adequate range.

Nilsson [21] investigated the running costs for estimation of the Specific Fan Power for Individual (SFPI) of typical air handling units of various sizes. The study established that the measured SFPI weighted by the investigated motors was found to be 1.5 $kWm^{-3}\,s^{-1}$ on average with the primary reason for performance reduction coming from contractors who do not spend time and money on commissioning of existing systems. The research concluded that there is a significant reduction in efficiency from the existing systems resulting in economic and performance losses. Fig. 7 displays the mechanism inside a typical air handling unit.

Rouleta et al. [23] studied the performance analysis of energy recovery with air-handling systems in order to determine the decrease in energy usage in building heating and cooling. The investigation found out that the air-handling units require a significant improvement in specifications since there is a decrease in efficiency with results confirming the efficiency in between 60% and 70% of heat recovery with the existing systems particularly in the form of fluid leakage. Further, the results confirm that units require an external energy usage to provide power for the fans which therefore limits the system to utilize more energy than it saves.

6. Complex techniques using advanced cooling cycles

6.1. Desiccant cooling systems

Desiccant cooling is a solar mechanical system that is fast growing as a passive cooling technology for sustainable HVAC in buildings since the primarily required form of energy is low-temperature heat which can either be supplied through waste heat or by optimal utilization of solar thermal energy. Fig. 8 displays the schematic of a simple desiccant cooling system. In a solar desiccation cooling cycle, energy from the sun is utilized to rejuvenate a desiccant that dehumidifies moist air; the resultant dry air is refrigerated in a sensible heat regenerator and then in an evaporative cooler [24]. Desiccant cooling is particularly useful for air-based cooling systems since they straightforwardly condition the inlet air into the building envelope. Bourdoukan et al. [24] carried out research on the overall performance of a desiccant air handling unit power-driven by vacuum-tube solar collectors. Moderately humid climatic conditions are taken up for the study since the desiccant cycle is dependent on operating parameters such as inlet and outlet temperatures and the humidity ratio. The study confirmed that the overall efficiency of the system is 55% while the coefficient of performance (COP) is found to be 0.45.

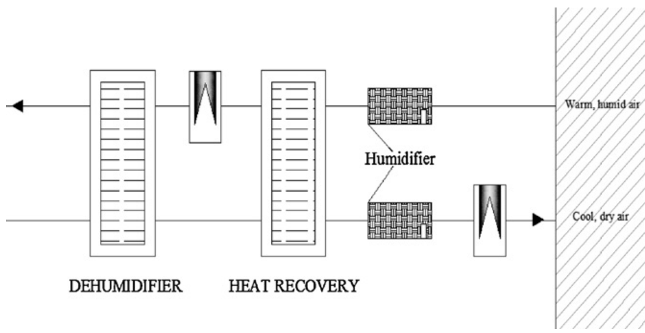


Fig. 8. Simplified desiccant cooling system schematic.

Dai et al. [25] established a hybrid air conditioning system to consist of divisions for evaporative cooling, desiccant dehumidification and vapor compression air conditioning. The research comprised of experimental techniques which confirmed that that the cooling production and the coefficient of power (COP) increased in comparison to the utilization of vapor compression system (VCS) individually in the range of 20–30%. The study concluded that the hybrid system's advantages included a reduction in the overall energy consumption along with a reduction in size of the VCS. Fong et al. [26] carried out work to improve the efficiency of basic solar desiccant cooling systems for conditioning office building utilities in Hong Kong. Six different kinds of hybrid designs were modeled for the investigation for fresh and return air zones. Under typical climatic changes, the evaluation on the designs was carried out. The study confirmed that all the 6 designs were environmentally feasible with a potential reduction of almost 35% obtained for external energy consumption compared to conventional air-cooled air-conditioning systems and 33% against the water-cooled systems. Ge et al. [27] carried out investigation in Shanghai Jiao Tong University on the two-stage desiccant cooling system on one-rotor using isothermal dehumidification process as displayed in Fig. 9. The results confirmed that the thermal COP



Fig. 9. One-rotor two-stage rotary desiccant cooling system in Shanghai Jiao Tong University [27].

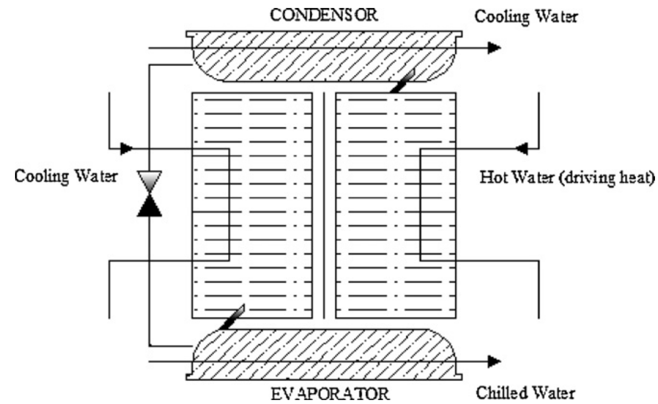


Fig. 10. Absorption cooling system schematic.

is almost 1 when the regeneration temperature is lower than 353 K.

6.2. Absorption cooling systems

Absorption cooling closed-cycle process as shown in Fig. 10 and is a technology that requires a refrigerant and an absorbent, with lithium bromide used as the most common refrigerant. The absorption system uses a system consisting of a heat exchanger, a pump, a generator and an absorber to boil the lithium bromide and water solution and to compress the vapor to high pressure. The pressure is lowered using a throttling valve, and the low pressure liquid is subjected into the evaporator and the boiling process takes place. Since the boiling temperature is less that the temperature of the conditioned air, heat transfer takes place from the conditioned air stream into the evaporator causing the liquid to boil and exclusion of heat from the air using this technique causes the air to cool down. The cooling result is based on the evaporation of water at low pressure [28].

Zhai and Wang [29] demonstrated work on the feasibility of using solar absorption and adsorption cooling systems in five major projects in China. The study found that solar absorption cooling systems implemented have a better feasibility in large building air conditioning systems whereas the solar adsorption cooling systems operate best with small-scale building air conditioning systems.

Florides et al. [30] studied the applicability of a medium sized solar absorption cooling system in comparison to a conventional cooling system in estimation of the total equivalent warming impact of the machines. The experimental design included an 11 kW solar cooling device. The numerical simulations were estimated using TRNSYS code. The results revealed that the system was economically reliable for satisfying the cooling demands of a commercial dwelling and the total life-cycle costs were estimated to be £13,380. The investigation further concluded that the solar absorption cooling system produced a lower warming impact than the conventional air-conditioning system.

Steam absorption chillers are the most recognizable kind of absorption chillers in the current market since it is readily available in combined heat and power plants. Alternatively, hot water at temperatures above 353 K can be utilized to drive a single-effect absorption chiller. The direct-fired unit can also be fired by propane, biogas, and fuel oil. In order to increase the efficiency of the system, direct-fired absorption chillers can be modified to accept hot air or exhaust gases from a gas turbine or engine. All these commercially available absorption chillers reject heat to a cooling tower circuit where in mostly the temperatures in the cool-



Fig. 11. Kawasaki commercialized triple-effect absorption chiller [32].

ing tower circuit is 305–310 K [31]. Fig. 11 displays the Kawasaki triple-effect absorption chiller operational in 2005 using reverse flow cycle. The thermal coefficient of performance of the unit is 1.6 and the reduction rate of fuel gas consumption is 20% in a rated cooling operation with an exhaust heat cogeneration system [32].

A further advanced cooling technology that has successfully resulted in reducing the heat gains of a building includes the use of Thermally Activated Building Systems. This arrangement uses pipes fixed onto the floor of the building which carry water for the rationale of heating and cooling. This was proved when Rijksen et al. [33] investigated the effectiveness of using TABS to reduce the cooling loads of an office building, 'The Thermo-state' in The Netherlands. The measurements included collection of the climatic conditions of the room along with the surface temperature of the floor mounted water pipes. The data was incorporated into a simulation model to predict the cooling capacity obtained from the technique under study. The research found out that nearly 50% of the cooling capability of a chiller can be obtained using TABS. It was also found out using numerical analysis that the size of windows has a significant influence on the cooling capacity of buildings.

7. Results summary

From the reviewed cooling technologies for buildings, it is considered that each system has its own advantages and limitations based largely on economic reserves and dynamic climatic conditions. Table 1 summarizes an outline of the relevant cooling technologies reviewed along with the electrical consumption and the measured values of the COP obtained from various case-studies and commercial manufacturers.

8. Discussion

8.1. Energy and COP analysis

Table 1 summarized the properties of principle cooling technologies which were obtained based on relevant case-studies. It is observed that the highest COP is obtained from implementing active or mechanical night ventilation for exhaust and supply air in the Ebök building in Germany. The case-study highlights that 85 Wh m^{-2} of internal loads were removed for every night on average for the two week investigation period. Since mechanical fans were utilized, the rate of electrical power consumption was considerable and the mean COP was recorded at 4.0.

Reviewing all the active and passive cooling technologies in this study, Table 1 displays that a wind tower can have zero COP since it operates on natural wind resource and does not require any mechanical components which consume power. This makes it a particularly useful passive technique for reducing cooling loads in buildings especially in unobstructed areas, where it can take advantage of higher wind velocity. The wind tower system can also be outfitted in areas receiving little or no wind, by making use of solar-powered fans to provide mechanical assistance for the flow through the device.

Limitations of implementing wind towers in buildings vary according to weather conditions at the location of the site. Pollutants and extreme weather conditions often result in reducing the comfort levels of the building space and increase the risk of air pollution. However, there are a number of sophisticated external components available on a global scale in order to increase the efficiency of the respective. Mechanical dampers are widely used to control the rate and direction of air flow entering into the building space. This mechanism is usually located upstream of the diffuser and the air vanes can be controlled either by hand or by mechanical means. By installing dampers beneath the windvent, the air flow

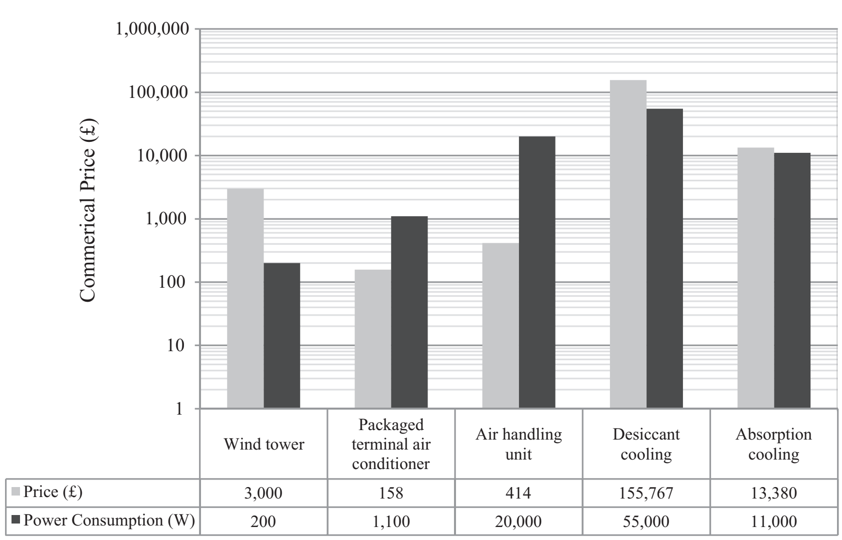


Fig. 12. Comparison of cost and power of the system on the log scale.

Table 1
Summary of the cooling technologies under review.

Cooling technique	Features	Limitations	Case-study	Commercial equipment	Typical COP	Investment cost (£)	Power consumption (W)	Ref.
Night ventilation	Active or passive cooling technique that works on natural ventilation.	Winds can cause polluted air to enter the space.	Ebök Building, Tübingen	Active ventilation in ebök building	4.0–6.0	N.A.	7400	[34]
Wind tower	No moving parts for the process of natural ventilation.	Higher velocity wind results in disorderly cooling temperatures.	Sheffield Hallam University, U.K.	Midtherm Ltd. Windvent	N.A.	£3,000	200	[16,35]
Packaged terminal air conditioner	Small sizes and easy to install.	High initial cost. Vibration and noise pollution.	Shanghai Jiao Tong University, Shanghai	GE Deluxe AGM12AJ Window AC	2.6	£158	1100	[36,37]
Air handling unit	Flexibility for heating and cooling individual rooms.	Oversized machines can cause short-cycling.	Tsinghua Low-Energy Building, Beijing	Kilmaire ARAM42H2P	1.3–1.8	£414	20,000	[34,38,39]
Desiccant cooling	Reduces the fossil fuel consumption causing savings in energy.	Additional heat exchanger decreases cooling power.	Mataró Public Library, Spain	Desiccant cooling unit, Mataró, Spain	0.6	£155,767	55,000	[34]
Absorption cooling	No contribution to global warming since water is used as a refrigerant.	Less overall efficiency compared to compression-driven chillers.	Basse Terre, Guadeloupe	Domestic size absorption cooling system, Cyprus	0.7	£13,380	11,000	[8,30]

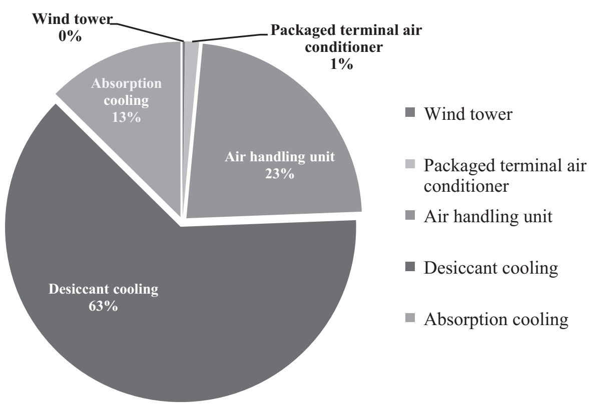


Fig. 13. Electricity consumption pie-chart for the reviewed cooling technologies.

can be controlled to meet the required comfort levels irrespective of the free-stream wind velocity.

8.2. Electricity consumption analysis

Table 1 displays the estimated costs of the already implemented commercial cooling technologies internationally. The cooling system with highest capital investment was found to be the desiccant cooling unit in Mataró, Spain with the collectors and the unit control for the building management system contributing 12% and 15%, respectively to the total expenditure. The plant was installed in a public library building having a surface area of 3500 m^2 to be cooled, thus the highest electrical power of 55 kW was achieved.

It was concluded that the most inexpensively viable option is to utilize small-scale air conditioning systems, which are less expensive to install and have an adequate cooling power as, displayed on a log arithmetic scale in Fig. 12.

However, with respect to Fig. 13, the external power consumption of the reviewed cooling technologies is displayed. It is observed that the electricity utilization of a desiccant cooling system is more than 60% when compared with other technologies. The electrical consumption for the wind tower was predominantly due to the solar-power fan for keeping the air flow rate at the desired level at low external wind velocities. Therefore, the wind tower can still be classified as a carbon-neutral passive cooling device unlike the rest since the electricity consumption is nearly 0% when in comparison with other cooling strategies.

8.3. Energy recovery

An effective alternative to reduce the building mechanical loads is by introducing heat recovery systems such as a heat-pipe heat recovery unit or a heat-pipe heat exchanger. Heat-pipe heat exchangers contain finned sealed pipes which do not require external electricity supplies and can be extremely consistent since it includes no moving parts. These air-to-air energy recovery systems are predominantly useful in building environments such as hospitals and laboratories which do not require mixing of fresh and stale air streams and thus manage thermal comfort levels of the building space.

9. Conclusion

Although a lot of advancements are made in active and passive cooling strategies, they have their own limitations based on either climatic variations or electricity expenditure. This investigation reviewed some of the common technologies in order to determine the economic and environmental viability. The study revealed that wind towers could be a source of the highest potential and capacity for reducing external electricity loads in buildings as it consumes minimal or no external power for its operation.

The study's conclusions are based on the research of various case-studies utilizing the cooling systems for their operations. Important parameters including the COP and power consumption are compared in order to determine the feasibility of implementing the devices for their respective use. In addition, the alternative utility of heat-pipe heat exchangers for air-to-air heat recovery in buildings is discussed to provide scope for future work.

Acknowledgements

This publication was made possible by a NPRP grant from the Qatar National research Fund (A member of the Qatar Foundation). The statements made herein are solely the responsibility of the authors. NPRP 09-138-2-059.

References

[1] Asif M, Muneer T, Kelley R. Life cycle assessment: a case study of a dwelling home in Scotland. Building and Environment 2007;42.
[2] Energy Efficiency in Buildings, World Business Council for Sustainable Development.
[3] Givoni B. Indoor temperature reduction by passive cooling systems. Solar Energy 2009.
[4] Allard F. Natural ventilation in buildings—a design handbook (p. 1–3), European Commission Directorate General for Energy Altener Program.
[5] BC Hydro, Centrifugal chillers [Online] 2010, [Cited September 20, 2010] Available from www.bchydro.com/./centrifugal_chillers.html.
[6] Becker R, Paciuk M. Inter-related effects of cooling strategies and building features in energy performance of office buildings. Energy and Buildings 2002;34:25–31.
[7] Natural ventilation concepts [Online] 2010 [cited October 3, 2010] Available from http://www.dyerenvironmental.co.uk/natural_vent_systems.html.
[8] Eicker U. Low energy cooling for sustainable buildings (p. 61–62), Stuttgart University of Applied Sciences, Germany.
[9] Ghiaus C, Allard F. Natural ventilation in the urban environment—assessment and design (p. 152–154), Earthscan.
[10] Geros V, Santamouris M, Karatasou S, Tsangrassoulis A, Papanikolaou N. On the cooling potential of night ventilation techniques in the urban environment. Energy and Buildings 2005;37:243–57.
[11] Wang Z, Yi L, Gao F. Night ventilation control strategies in office buildings. Solar Energy 2009;83:1902–13.
[12] Liu Lia CM, Mak B. The assessment of the performance of a windcatcher system using computational fluid dynamics. Building and Environment 2007;42:1135–41.
[13] Montazeri H, Azizian R. Experimental study on natural ventilation performance of one-sided wind catcher. Building and Environment 2008;43:2193–202.
[14] Hughes BR, Ghani SA. numerical investigation into the effect of windvent dampers on operating conditions. Building and Environment 2009;44:237–48.
[15] Hughes BR, Ghani SA. Investigation of a windvent passive ventilation device against current fresh air supply recommendations. Energy and Buildings 2008;40:1651–9.
[16] Hughes BR, Ghani SA. A numerical investigation into the feasibility of a passive-assisted natural ventilation stack device, International Journal of Sustainable Energy.
[17] Hughes BR, Ghani SA. A numerical investigation into the effect of windvent louvre external angle on passive stack ventilation performance. Building and Environment 2010;45:1025–36.
[18] Yika FWH, Burnetta J, Prescottb I. Predicting air-conditioning energy consumption of a group of buildings using different heat rejection methods. Energy and Buildings 2001;33:151–66.
[19] Zhao X, Yang S, Duan Z, Riffat SB. Feasibility study of a novel dew point air conditioning system for China building application. Building and Environment 2009;44:1990–9.
[20] Kusiak A, Li M. Cooling output optimization of an air handling unit. Applied Energy 2010;87:901–9.
[21] Nilsson LJ. Air-handling energy efficiency and design practices. Energy and Buildings 1995;22:1–13.
[22] Yang D. Air-conditioning, air handling unit [Online] 2010 [Cited September 20, 2010]. Available from http://hvacdac.com/english/product_show.html?code=01010000&uid=4.
[23] Rouleta C-A, Heidtb FD, Foradinic F, Pibiria M-C. Real heat recovery with air handling units. Energy and Buildings 2001;33:495–502.
[24] Bourdoukan P, Wurtz E, Joubert P. Experimental investigation of a solar desiccant cooling installation. Solar Energy 2009;83:2059–73.
[25] Dai YJ, Wang RZ, Zhang HF, Yu JD. Use of liquid desiccant cooling to improve the performance of vapor compression air conditioning. Applied Thermal Engineering 2001;21:1185–202.
[26] Fong KF, Chow TT, Lee CK, Lin Z, Chan LS. Advancement of solar desiccant cooling system for building use in subtropical Hong Kong. Energy and Buildings 2010;42:2386–99.
[27] Ge TS, Dai YJ, Wang RZ, Li Y. Experimental investigation on a one-rotor two-stage desiccant cooling system. Energy 2008;33(12):1807–15.
[28] How absorption cooling works [Online] 2010 [cited September 20, 2010]. Available from http://www.gasairconditioning.org/absorption_how_it_works.htm.
[29] Zhai XQ, Wang RZ. A review for absorption and adsorption solar cooling systems in China. Renewable and Sustainable Energy Reviews 2009;13:1523–31.
[30] Florides GA, Kalogirou SA, Tassou SA, Wrobel LC. Modelling, simulation and warming impact assessment of a domestic-size absorption solar cooling system. Applied Thermal Engineering 2002;22:1313–25.
[31] Deng J, Wang RZ, Han GY. A review of thermally activated cooling technologies for combined cooling, heating and power systems. Progress in Energy and Combustion Science 2010:1–32.
[32] Makita K. Development and commercialization of triple-effect absorption chiller–heaters. IEA Heat Pump Centre Newsletter 2006;24(1):20–3.
[33] Rijksen DO, Wisse CJ, van Schijndel AWM. Reducing peak requirements for cooling by using thermally activated building systems. Energy and Buildings 2010;42:298–304.
[34] Industrial Technologies Program Energy Efficiency and Renewable Energy U.S. Department of Energy Washington, DC, 20585-0121 http://www.eere.energy.gov/industry.
[35] Midtherm Engineering Ltd. [Online] 2010 [cited October 4, 2010]. Available from http://www.naturallydriven.co.uk/index.php.
[36] Wang S, Liu Z, Li Y, Zhao K, Wang Z. Experimental study on split air conditioner with new hybrid equipment of energy storage and water heater all year round. Energy Conversion and Management 2005;46:3047–59.
[37] GE Deluxe AGM12AJ Window AC, DIY Trade [Online] 2010 [cited October 3, 2010]. Available from http://www.diytrade.com/china/4/products/2448229/GE_Deluxe_AGM12AJ_Thru-Wall_Window_Air_Conditioner.html.
[38] Xie X, Jiang Y, Tang Y, Yi X, Liu S. Simulation and experimental analysis of a fresh air-handling unit with liquid desiccant sensible and latent heat recovery, Department of Building Science, Tsinghua University, Beijing 100084, China.
[39] Facotry Outlet, Kilmaire Products [Online] 2010 [cited October 3, 2010] Available from http://www.heatandcool.com/ProductDetails.asp?ProductCode=ARAM42H2P&utm_source=pricegrabber&utm_medium=comparisonshopping.